JLAB-THY-08-815

Electromagnetic and strong contributions to dAu soft coherent inelastic diffraction at RHIC

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Abstract

We estimate electromagnetic (ultra-peripheral) and strong contributions to dAu soft coherent inelastic diffraction at RHIC, $dAu \to XAu$. We show that the electromagnetic contribution is the dominant one and that the corresponding cross section is sizable, $\sigma_{\rm e.m.}^{dAu \to XAu} = 214$ mb, which constitutes 10% of the total dAu inelastic cross section.

PACS numbers: 24.20.Ht, 25.45.De, 25.75.-q

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Deuteron – Gold (dAu) collisions constitute an essential part of the present physics program of the Relativistic Heavy Ion Collider (RHIC). Ultra-peripheral collisions (UPC) of ions of deuterium and Gold (or any other ions) are processes, where the colliding nuclei are separated by the transverse distance (impact parameter) larger than the sum of the deuteron and Gold radii. In this case, the heavier ion of Au acts as a source of quasi-real photons of a very high energy (the photon flux produced by deuterium is negligibly small compared to that by Au) and, hence, one effectively studies the interaction of photons with deuterons, $dAu \to d\gamma Au \to XAu$ [1, 2].

At RHIC, dAu ultra-peripheral collisions were studied in the following channels: $dAu \to dAu\rho^0$ and $dAu \to npAu\rho^0$ [3], and $dAu \to npAu$ [4]. The cross section of the latter reaction was normalized to the theoretical prediction, $\sigma^{dAu\to npAu} = 1.38$ b [5]. This value is large and should be compared to the measured total dAu inelastic cross section, $\sigma^{dAu\to X} = 2.26$ b [1]. Since $\sigma^{dAu\to npAu}$ is so large, the $dAu \to npAu$ yield was used to determine the absolute normalization of the RHIC dAu data.

In this paper, we consider yet another channel of dAu UPC, namely, deuteron inelastic diffraction, $dAu \to d\gamma Au \to XAu$, where X denotes products of the deuteron inelastic dissociation. We find that the corresponding cross section is sizable, $\sigma_{\text{e.m.}}^{dAu\to XAu} = 214$ mb, which constitutes 10% of the total dAu inelastic cross section.

Although the discussed cross section is only $\sim 10\%$ of the total inelastic cross section, it may contribute a larger fraction of the signal in certain cases. For example, if one considers the leading pion or nucleon production at small transverse momenta p_t, one observes that the multiplicity of such processes is about the same in pN and γN interactions. At the same time, the A-dependence of the forward hadron multiplicity for $x_F > 0.4$ (x_F is the fraction of the projectile's momentum carried by the leading hadron) is $\approx A^{-1/3}$. Hence the γN and pN interactions can give comparable contributions in the considered case.

We also estimate the strong contribution to $dAu \to XAu$ soft coherent inelastic diffraction and find that the corresponding cross section is rather small, $\sigma_{\text{dd}}^{dAu\to XAu} = 22$ mb.

The cross section of deuteron inelastic diffraction in dAu ultra-peripheral scattering reads, see e.g. [1, 2],

$$\sigma_{\text{e.m.}}^{dAu\to XAu}(s) = 2 \int_{\omega_{\min}}^{\omega_{\max}} d\omega \, \frac{dN_\gamma(\omega)}{d\omega} \, \sigma_{\text{tot}}^{\gamma p}(\omega) \,, \tag{1}$$

where $dN_\gamma(\omega)/d\omega$ is the flux of equivalent photons emitted by Au; $\sigma_{\text{tot}}^{\gamma p}(\omega)$ is the total real

photon-nucleon cross section; s is the total invariant energy squared per nucleon ($\sqrt{s} = 200$ GeV at the present RHIC energy); ω is the photon energy in the deuteron rest frame; $\omega_{\rm max}$ and $\omega_{\rm min}$ are the maximal and minimal values of ω (see below). The factor of two is the reflection that the total photon-deuteron cross section is twice the total photon-proton cross section. Note that Eq. (1) is implicitly invariant with respect to boosts along the collision axis. We will work in the deuteron rest frame.

In Eq. (1), the flux of equivalent photons emitted by the fast nucleus of Au is [1, 2]

$$\begin{aligned} \frac{dN_\gamma(\omega)}{d\omega} &= \frac{Z^2\alpha\omega}{\pi^2\gamma^2}\int_{|b|>R_A+R_d} d^2b \left[K_1^2\left(\frac{\omega|b|}{\gamma}\right) + \frac{1}{\gamma^2}K_0^2\left(\frac{\omega|b|}{\gamma}\right)\right] \\ &= \frac{2\,Z^2\alpha}{\pi\omega}\left[xK_0(x)K_1(x) + \frac{x^2}{2}\left(K_0^2(x) - K_1^2(x)\right)\right] \,, \end{aligned} \tag{2}$$

where Z is the electric charge ($Z = 79$ for Au); $\alpha \approx 1/137$ is the fine-structure constant; γ is the Lorentz factor of the fast moving Au; b is the distance between the centers of Au and the deuteron in the transverse plane (impact parameter), which should be larger than the sum of the corresponding Au and deuteron radii, R_A and R_d; K_0 and K_1 are modified Bessel functions; $x = (R_A + R_d)\omega/\gamma$. Note also that we omitted the negligibly small contribution of the K_0^2/γ^2 term, when going from the first to the second line of Eq. (2).

The maximal energy of the exchanged photon, $\omega_{\rm max}$, is determined by the Lorentz-contracted nuclear size, $\omega_{\rm max} = \gamma/R_A$. The minimal photon energy, $\omega_{\rm min}$, is termined by the threshold of the inelastic $\gamma + p \to \Delta(1232)$ reaction. In the proton rest frame, $\omega_{\rm min} = 0.3$ GeV.

For the evaluation of $\sigma_{\rm e.m.}^{dAu\to XAu}$ using Eq. (1), we used the following input. At the current RHIC energy of $\sqrt{s} = 200$ GeV per nucleon, the Lorentz factor of Au in the deuteron rest frame is $\gamma = 2.3 \times 10^5$. The Au ($A = 197$) effective radius was parameterized in a simple form, $R_A = 1.145\,A^{1/3} \approx 6.7$ fm. Therefore, the maximal photon energy is $\omega_{\rm max} = 670$ GeV. For the deuteron radius, we used $R_d = 1.88$ fm, which was obtained using the deuteron wave function with the Paris nucleon-nucleon potential [6]. We checked that the result of Eq. (3) does not change, if we vary R_d by 1 fm in order to mimic the effect of fluctuations of the size of the proton-neutron system in the deuteron. For the real photon-proton cross section, we used the ALLM parameterization [7].

Figure 1 presents the integrand of Eq. (1), $2\sigma_{\rm tot}^{\gamma p}(\omega)dN_\gamma(\omega)/d\omega$, as a function of the photon energy ω in the deuteron rest frame.

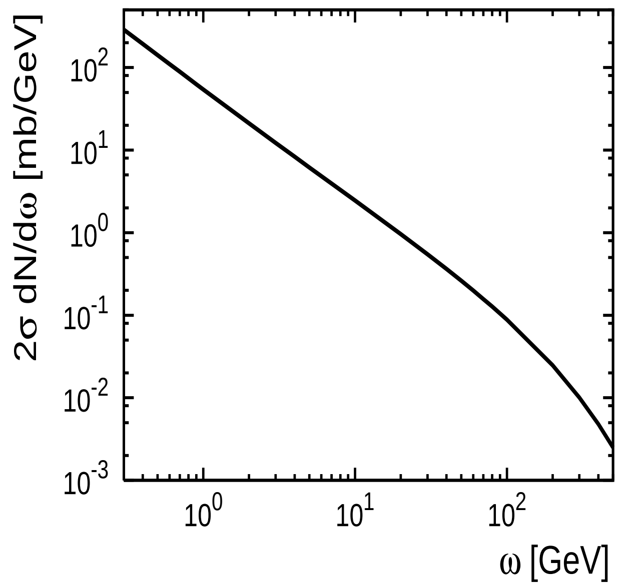

FIG. 1: The integrand of Eq. (1), $2\sigma_{\rm tot}^{\gamma p}(\omega) dN_{\gamma}(\omega)/d\omega$, as a function of the photon energy ω in the deuteron rest frame.

A direct evaluation of Eq. (1) using the input described above gives

$$\sigma_{\rm e.m.}^{dAu \to XAu} = 214 \ {\rm mb} \,. \tag{3}$$

This value is quite sizable: it constitutes 10% of the total dAu inelastic cross section, $\sigma^{dAu \to X} = 2.26$ b [1].

The application of Eq. (1) to inelastic diffraction in deuteron-Lead UPC at the LHC energy ($\sqrt{s} = 6.2$ TeV) gives $\sigma_{\rm e.m.}^{dPb \to XPb} = 828$ mb.

The value of $\sigma_{\rm e.m.}^{dAu \to XAu}$ can be compared to the cross section of $dAu \to XAu$ soft coherent inelastic diffraction, $\sigma_{\rm dd}^{dAu \to XAu}$, which is due to the strong interaction. This cross section can be calculated based on the concept of cross section fluctuations [8, 9]. Within this formalism, an analysis of various phenomena involving proton-proton and proton-deuteron scattering allowed to determine the distribution over the strength of the interaction [10], which lead to the explanation of cross sections of inelastic diffraction of protons and pions off nuclei at fixed-target energies [11, 12]. For a summary and extension to collider energies, see [13, 14]. Below we outline the derivation of $\sigma_{\rm dd}^{dAu \to XAu}$.

In the standard Glauber method [15, 16], inelastic diffraction is absent and the only two allowed diffractive final states in coherent dAu scattering are elastic, $dAu \to dAu$, and

deuteron dissociation, $dAu \to pnAu$. Using the completeness of these two diffractive states, the sum of the corresponding cross sections can be expressed as

$$\sum_{X=d,pn} \sigma^{dAu\to XAu} = \int d^2b\, d^2r_t\, |\psi_D(r_t)|^2$$
$$\times \left| \left(1 - \exp\left[-\frac{\sigma_{\rm tot}^{pN}}{2} T\left(b+\frac{r_t}{2}\right) - \frac{\sigma_{\rm tot}^{nN}}{2} T\left(b-\frac{r_t}{2}\right) + \sigma_{\rm el}^{NN} e^{-r_t^2/(4B_{\rm el})} T(b) \right] \right) \right|^2 . \qquad (4)$$

In this equation, b is the transverse distance between the centers of Au and d; r_t is the transverse distance between the proton and neutron in the deuteron; $\psi_D(r_t)$ is the deuteron wave function; $\sigma_{\rm tot}^{pN}$ and $\sigma_{\rm tot}^{nN}$ are respectively the proton-nucleon and neutron-nucleon total scattering cross sections (for the purpose of the following discussion, it is convenient to distinguish between the two cross sections); $\sigma_{\rm el}^{NN}$ is the elastic nucleon-nucleon (NN) cross section; $B_{\rm el}$ is the slope of the NN elastic amplitude; $T(b)$ is the so-called optical density of the nucleus of Au, $T(b) = \int dz \rho_A(r)$, where $\rho_A(r)$ is the nuclear density [17]. The real part of the NN scattering amplitude is neglected in Eq. (4).

In the following analysis, we neglect the contribution of the last term in the exponent in Eq. (4), which is suppressed by the smallness of the elastic cross section, $\sigma_{\rm el}^{NN}/\sigma_{\rm tot}^{NN} \approx 1/5$ at $\sqrt{s} = 200$ GeV, and by the smallness of the $e^{-r_t^2/(4B_{\rm el})}$ factor, $e^{-r_t^2/(4B_{\rm el})} \approx 0.15$ at $r_t = 2$ fm and $B_{\rm el} = 13$ GeV^{-2}.

In order to take into account inelastic diffraction of deuterons, the standard Glauber method can be complemented by the formalism of cross section fluctuations. In the combined approach, the $dAu \to XAu$ coherent inelastic diffractive (diffraction dissociation) cross section reads

$$\sigma_{\rm dd}^{dAu\to XAu} = \int d^2b\, d^2r_t\, |\psi_D(r_t)|^2$$
$$\times \left\{ \int d\sigma_p P(\sigma_p) d\sigma_n P(\sigma_n) \left| \left(1 - \exp\left[-\frac{\sigma_p}{2} T\left(b+\frac{r_t}{2}\right) - \frac{\sigma_n}{2} T\left(b-\frac{r_t}{2}\right) \right] \right) \right|^2 \right.$$
$$\left. - \left| \int d\sigma_p P(\sigma_p) d\sigma_n P(\sigma_n) \left(1 - \exp\left[-\frac{\sigma_p}{2} T\left(b+\frac{r_t}{2}\right) - \frac{\sigma_n}{2} T\left(b-\frac{r_t}{2}\right) \right] \right) \right|^2 \right\} , \qquad (5)$$

where the proton and neutron of the deuteron interact with the target nucleons with the total cross sections σ_p and σ_n, whose probability distributions are given by $P(\sigma_p)$ and $P(\sigma_n)$, respectively. The distribution $P(\sigma)$ is peaked around the total NN cross section with a small

dispersion. This allows one to expand the exponents in Eq. (5) around $\sigma_{\rm tot}^{NN}$ [11] and to obtain

$$\sigma_{\rm dd}^{dAu\to XAu} = \frac{(\sigma_{\rm tot}^{NN})^2\,\omega_\sigma}{4}\,2\int d^2b\,d^2r_t\,|\psi_D(r_t)|^2\left[T\left(b+\frac{r_t}{2}\right)\right]^2 \times\ \exp\left[-\sigma_{\rm tot}^{NN}\left(T\left(b+\frac{r_t}{2}\right)+T\left(b-\frac{r_t}{2}\right)\right)\right]\,, \tag{6}$$

where ω_σ is a parameter describing the dispersion of $P(\sigma)$ around its maximum and is proportional to $\sigma_{\rm dd}^{NN\to XN}$, the cross section of inelastic diffraction in NN scattering. At $\sqrt{s}=200$ GeV, ω_σ is maximal, $\omega_\sigma=0.3$ [14]. The factor of two in front of the integral in Eq. (6) is a sum of the proton and neutron contributions. Note that we do not distinguish the proton-nucleon and neutron-nucleon cross sections in Eq. (6).

The physical interpretation of Eq. (6) is the following. Inelastic diffraction of deuterons receives independent and equal contributions from inelastic diffraction of the proton and neutron of the deuteron. The contribution, when both the proton and neutron diffract, is small and has been neglected. Let us consider the contribution due to the proton diffraction. At high energies, the internal motion of nucleons in the deuteron and in the nucleus of Au is Lorentz dilated and, hence, the nucleons can be considered "frozen" in the their transverse positions. The proton of the deuteron at the position $\vec{b}+\vec{r_t}/2$ undergoes inelastic diffraction with the probability proportional to $[T\,(b+r_t/2)]^2\,\exp(-\sigma_{\rm tot}^{NN}T\,(b+r_t/2))$. At the same time, the neutron at the position $\vec{b}-\vec{r_t}/2$ does not take part in the interaction. The probability for the neutron to not interact is $\exp(-\sigma_{\rm tot}^{NN}\,T\,(b-r_t/2))$. An equal contribution to the deuteron inelastic diffraction comes from the situation, when the proton and neutron switch roles. The two contributions are schematically presented in Fig. 2.

A direct evaluation of Eq. (6) gives

$$\sigma_{\rm dd}^{dAu\to XAu}=22\ {\rm mb}\,. \tag{7}$$

In our calculation, we used the Paris deuteron wave function [6] and the parameterization of $\sigma_{\rm tot}^{NN}$ due to Donnachie and Landshoff [18].

We would like to note that various channels of dAu scattering in the RHIC kinematics using the Glauber method combined with the dipole formalism (which leads to cross section fluctuations) were considered in [19]. However, soft coherent inelastic diffraction or ultra-peripheral collisions were not addressed.

In summary, we estimated deuteron inelastic diffraction in ultra-peripheral $dAu\to d\gamma Au\to XAu$ scattering, when the ion of Au serves as a source of high-energy photons.

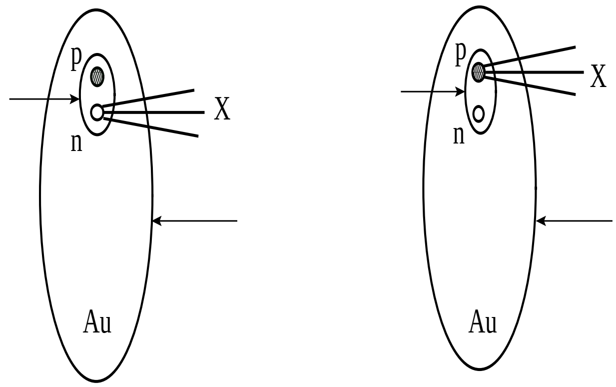

FIG. 2: The schematic representation of $dAu \to XAu$ coherent inelastic diffraction as a sum of two contributions, when either the neutron (left picture) or the proton (right picture) diffracts inelastically.

We found that the corresponding cross section is sizable, $\sigma_{\rm e.m.}^{dAu\to XAu} = 214$ mb, which constitutes 10% of the total dAu inelastic cross section. The same reaction can also proceed through the strong interactions. We derived an approximate expression for the cross section of $dAu \to XAu$ soft coherent inelastic diffraction and estimated it to be rather small, $\sigma_{\rm dd}^{dAu\to XAu} = 22$ mb.

We also estimated the cross section of deuteron-Lead inelastic diffraction in ultraperipheral $dPb \to d\gamma Pb \to XPb$ scattering at the LHC energies ($\sqrt{s} = 6.2$ TeV) and found $\sigma_{\rm e.m.}^{dPb\to XPb} = 828$ mb. The corresponding cross section of $dPb \to XPb$ soft coherent inelastic diffraction due to the strong interactions is negligibly small, $\sigma_{\rm dd}^{dAu\to XAu} = 7$ mb, due to the vanishingly small $NN \to XN$ inelastic diffraction.

We want to thank Sebastian White for useful discussions and Boris Kopeliovich for explanations of the results of Ref. [19]. The work of M.S. is supported by DOE.

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